THREE-DIMENSIONAL IMAGING DEVICE

BY

DONG WOO GIM ET AL.

BACKGROUND OF THE INVENTION

The present invention relates to a three-dimensional imaging device using a micromirror array lens.

Several three-dimensional imaging devices have been proposed and developed. One of them uses a "depth from focus" criterion and fast response variable focal length lens. It is described in T. Kaneko et al., 2000, "Quick Response Dynamic Focusing Lens using Multi-Layered Piezoelectric Bimorph Actuator," *Proceeding of SPIE* Vol. 4075: 24-31. This imaging system uses a variable focal length lens comprised of two thin glass diaphragms with a transparent working fluid and multi-layered piezoelectric bimorph actuator mounted thereon. To get a three-dimensional image, the criterion of "depth from focus" achieves an all-in-focus image and three-dimensional reconstruction, simultaneously. Since the variable focal length lens has a slow focal length change speed of 150 Hz, the system can have only 5 focal plane shifts when about 30 Hz is considered for the afterimage effect of the human eye. Besides, the lens has a small focal plane variation in the

range of -4 mm to 4 mm, which limits the possible range of depth and the depth resolution of the three-dimensional image. A high speed, large variation of numerical aperture and large diameter of variable focal length lens is necessary to get a real-time, large range of depth and high depth resolution three-dimensional image.

A most widely used conventional variable focusing system is the one using two refractive lenses. It has a slow response time and complex driving mechanisms to control the relative position of the refractive lenses. Alternatively, variable focal length lenses have been made. Among them, a most advanced variable focal length lens is a liquid crystal variable focal length lens, which has a complex mechanism to control it. Its focal length is changed by modulating the refractive index. Unfortunately, it has a slow response time typically on the order of hundreds of milliseconds. Even though the fastest response liquid crystal lens has a response time of tens of milliseconds, it has a small focal length variation and a low focusing efficiency.

A new three-dimensional imaging device is needed to overcome the problems of the prior arts that used variable focal length lenses that are slow, have small focal length

variation and low focusing efficiency, and/or have a complex control mechanism.

SUMMARY OF THE INVENTION

An objective of the invention is to provide a real-time three-dimensional imaging system that can get an all-in-focus image and depth information of the image.

Another objective of the invention is to provide a three-dimensional imaging system that can compensate various optical distortions or aberrations.

The present invention provides a real-time three-dimensional imaging device with a large depth range using a variable focal length micromirror array lens.

The three-dimensional imaging device generates an all-in-focus image and depth information of the image. The device includes a variable focal length lens, an imaging unit capturing images with different focal planes, which are changed by the variable focal length lens, and an image processing unit processing the images.

The variable focal length lens comprises a micromirror array lens.

The focal plane of the imaging device is changed by change of focal length of the micromirror array lens.

The imaging unit includes one or more two-dimensional image sensor taking an original two-dimensional image at each focal plane.

The image processing unit generates the all-in-focus image and the depth information for in-focus image from original two-dimensional images. All the processes are achieved within a unit time which is less than or equal to the afterimage time of the human eye.

The image sensor takes original two-dimensional images with different focal planes that are shifted by changing the focal length of the micromirror array lens. The image processing unit extracts in-focus pixels or areas from original pictures at different focal planes and generates an all-in-focus image. Three-dimensional information of the image can be obtained from the focal plane of each in-focus pixel. There are several methods for the image processing unit to obtain an all-in-focus image with depth information. Recent advances in both the image sensor and the image processing unit make them as fast as they are required to be.

The micromirror array lens includes a plurality of micromirrors. The translation and/or rotation of each micromirror of the micromirror array lens is controlled to change the focal length of the lens.

The micromirrors of the micromirror array lens are arranged to form one or more concentric circles.

Each micromirror of the micromirror array lens may have a fan shape.

The reflective surface of each micromirror of the micromirror array lens is substantially flat. Alternatively, the reflective surface of each micromirror of the micromirror array lens can have a curvature. The curvature of the micromirror can be controlled.

Preferably, the reflective surface of the micromirror is made of metal.

Each micromirror of the micromirror array lens is actuated by electrostatic force and/or electromagnetic force.

The micromirror array lens further includes a plurality of mechanical structures upholding the micromirrors and actuating components for actuating the micromirrors. The mechanical structures and the actuating components are located under the micromirrors.

The micromirror array lens is a reflective Fresnel lens, and the micromirrors are arranged in a flat plane. Each micromirror has the same function as a mirror. The array of micromirrors works as a reflective focusing lens by making all light scattered from one point of an object

have the same periodical phase and converge at one point on the image plane. In order to do this, the micromirrors are electrostatically and/or electromagnetically controlled by actuating components to have desired positions. The focal length of the lens is changed by controlling its translation, by controlling its rotation, or by controlling both translation and rotation.

The three-dimensional imaging system includes a beam splitter positioned between the micromirror array lens and an image sensor. Alternatively, the micromirror array lens is positioned so that the path of the light reflected by the micromirror array lens is not blocked without using a beam splitter.

The micromirror array lens is an adaptive optical component. The micromirror array lens compensates for phase errors of light introduced by the medium between an object and its image and/or corrects the defects of the three-dimensional imaging system that may cause the image to deviate from the rules of paraxial imagery. Also, an object which does not lie on the optical axis can be imaged by the micromirror array lens without macroscopic mechanical movement of the three-dimensional imaging system.

In order to obtain a color image, the micromirror array lens is controlled to satisfy the same phase

condition for each wavelength of Red, Green, and Blue (RGB), respectively. The three-dimensional imaging system may further include a plurality of bandpass filters for color imaging. Also, the three-dimensional imaging system may further include a photoelectric sensor. The photoelectric sensor includes Red, Green, and Blue (RGB) sensors. A color image is obtained by processing electrical signals from the Red, Green, and Blue (RGB) sensors according to an imaging processing method. The processing of electrical signals from the Red, Green and Blue (RGB) sensors is synchronized and/or matched with the control of the micromirror array lens to satisfy the same phase condition for each wavelength of Red, Green and Blue (RGB), respectively.

The micromirror array lens includes micromirrors and actuating components, and uses a very simple mechanism to control the focal length. The focal length of the micromirror array lens is changed with the translation and/or rotation of each micromirror.

The micromirror has a tiny mass. Therefore, the lens comprising the micromirror has a very fast response time down to hundreds of microseconds. The lens also has a large focal length variation and a high optical focusing efficiency. In addition, the lens design makes a large size lens possible, makes the focusing system very simple, and

requires low power consumption. The lens has a low production cost because of the advantage of mass productivity. The lens can also compensate for optical effects introduced by the medium between the object and its image and/or corrects the defects of a lens system that cause the image to deviate from the rules of paraxial imagery.

The micromirror array lens can have a polar array of micromirrors. For the polar array, each micromirror has a fan shape to increase its effective reflective area so that the optical efficiency is increased. The aberration of the micromirror array lens can be reduced by micromirrors with curvatures. The optical efficiency of the micromirror array lens also can be increased by locating a mechanical structure upholding the micromirror and the actuating components under the micromirror to increase an effective reflective area and controlling the curvature of micromirrors.

The micromirror array lens used in the present invention has the following advantages: (1) the micromirror array lens has a very fast response time because each micromirror has a tiny mass; (2) the lens has a large focal length variation because large numerical aperture variations can be achieved by increasing the maximum

rotational angle of the micromirror; (3) the lens has a high optical focusing efficiency; (4) the lens can have a large size aperture without losing optical performance. Because the micromirror array lens includes discrete micromirrors, the increase of the lens size does not enlarge the aberration caused by shape error of a lens; (5) the cost is inexpensive because of the advantage of mass productivity of microelectronics manufacturing technology; (6) the lens can compensate for phase errors introduced by the medium between the object and the image and/or corrects the defects of the lens system that cause its image to deviate from the rules of paraxial imagery; (7) the lens makes the focusing system much simpler; (8) the lens requires small power consumption when electrostatic actuation is used to control it.

The three-dimensional imaging system of the present invention has the following advantages: (1) the device can make a real-time three-dimensional image; (2) the device has a large range of depth; (3) the device has a high optical efficiency; (4) the device can have high depth resolution; (5) the cost is inexpensive because the micromirror array lens is inexpensive; (6) the device can compensate for phase errors introduced by the medium between the object and its image and/or correct the defects

of a lens system that cause the image to deviate from the rules of paraxial imagery; (7) the device is very simple because there is no macroscopic mechanical displacement or deformation of the lens; (8) the device is compact; (9) the device requires small power consumption when the micromirror array lens is actuated by electrostatic force.

Although the present invention is briefly summarized herein, the full understanding of the invention can be obtained by the following drawings, detailed description, and appended claims.

DESCRIPTION OF THE FIGURES

These and other features, aspects and advantages of the present invention will become better understood with reference to the accompanying drawings, wherein:

FIG. 1 is a schematic diagram showing how a three-dimensional image is obtained from original two-dimensional images with different focal planes, which are obtained by changing the focal length of a micromirror array lens.

FIG. 2 is a schematic diagram showing a three-dimensional imaging device using the micromirror array lens.

FIG. 3 is a schematic diagram showing the three-dimensional imaging device using a beam splitter and the micromirror array lens.

FIG. 4 shows the principle of the micromirror array lens.

FIG. 5 is a schematic plan view showing the structure of the lens that is made of many micromirrors and actuating components.

FIG. 6 is a schematic diagram showing how a micromirror array lens works as a lens.

FIG. 7 is a schematic diagram showing the three-dimensional imaging device using an auxiliary lens.

DETAILED DESCRIPTION OF THE INVENTION

FIG. 1 shows how a micromirror array lens **1** gets original two-dimensional images **2A, 2B, 2C** with different focal planes **3A, 3B, 3C**. The micromirror array lens **1** includes many micromirrors **4**. The focal length of the micromirror array lens **1** is changed by electrostatically and/or electromagnetically controlling each of the micromirrors **4**. A focal length change of the micromirror array lens **1** changes the focal plane of the imaging system. Two-dimensional original images **2A, 2B, 2C** are taken with the depth information which is obtained from the position of the focal plane. The original two-dimensional image **2A** with the first focal plane **3A** has in-focus image **LI** which is the image of the portion **L** of an object **5**. Images **MD, ND**

of portion **M, N** of an object **5** are defocused. Therefore, the image processing unit determines the in-focus pixels **LI** from the original two-dimensional images **2A.** The focal plane **3A** of the first original two-dimensional image **2A** gives the depth information of in-focus pixels **LI.** The original two-dimensional images **2B, 2C** with the second and third focal plane **3B, 3C** are processed in the same manner as the first focal plane to get in-focus images and depth information of in-focus images.

An example of a micromirror array lens is described in the paper entitled "Fast-response Variable Focusing Micromirror Array Lens" by James G. Boyd IV and Gyoungil Cho, which was published on March 2, 2003. The paper is incorporated by reference into this disclosure as if fully set forth herein.

Fig. 2 shows a three-dimensional imaging device **6,** which takes an all-in-focus image **11** and depth information of the image. The device includes a variable focal length lens **7,** an imaging unit **8** capturing images **10** with different focal planes which are changed by the variable focal length lens **7,** and an image processing unit **9** processing the images **10.**

The focal plane of the imaging device is changed by change of focal length of the micromirror array lens **7.**

The imaging unit **8** includes one or more two-dimensional image sensor taking original two-dimensional images **10** with different focal planes.

The image processing unit **9** generates the all-in-focus image and the depth information for in-focus image from original two-dimensional images. All the processes are achieved within a unit time which is less than or equal to the afterimage time of the human eye.

When the micromirror array lens **7** changes the focal length according to the predetermined desired depths, the image sensor **8** takes original two-dimensional images **10** with the corresponding depth information. The desired number of depths is determined by the depth resolution and the range of depth of the object to be imaged. To get real-time three-dimensional video images, the desired focal planes are scanned within the unit time. Even though the unit time is not a serious problem for a still image, it must be less than the afterimage time of human eye for real-time three-dimensional video image. The necessary focal length change speed of the micromirror array lens is the desired number of focal planes times the afterimage speed of human eye. The necessary speed of the image processing is equal to or lager than the speed of micromirror array lens to do real-time three-dimensional

imaging. There are several methods for the image processing to obtain all-in-focus image **11** and depth information for each pixel of the image.

FIG. 3 shows an alternative arrangement in which the three-dimensional imaging device **12** further includes a beam splitter **13** positioned in the path of light between the micromirror array lens **14** and the image sensor **15.** Since the micromirror array lens **14** is a reflective type, the device **12** cannot be aligned in a line. An optical arrangement in which the reflected light is not blocked by the object **16** is required. The beam splitter **13** changes the direction of the light by 90°, and thus the micromirror array lens is positioned orthogonal to the light path.

Alternatively, as shown in FIG. 2, the micromirror array lens **7** is positioned so that the path of the light reflected by the micromirror array lens **7** is not blocked without using a beam splitter.

FIG. 4 shows the principle of a micromirror array lens **17**. There are two conditions for a perfect lens. The first is a converging condition that all light scattered by one point of an object should converge into one point of the image plane. The second is the same phase condition that all the converging light should have same phase at the image plane. To satisfy the perfect lens conditions, the

surface shape of conventional reflective lens **18** is generated to have all light scattered from one point of an object to be converged into one point on the image plane and have the optical path length of all the converging light to be same. Even though the optical path length of the converging light is different, the same phase condition can be satisfied because a phase of light is periodic. Therefore, the surface shape of the conventional reflective lens **18** satisfying perfect lens conditions can be replaced by rotation and translation of micromirrors. Each micromirror **19** rotates to converge the scattered light and translates to adjust the phase.

Fig. 5 illustrates the two-dimensional view of a micromirror array lens **20**. Each micromirror **21** of the micromirror array lens **20** is electrostatically and/or electromagnetically controlled by actuating components **22**. Because a lens is axisymmetric, the micromirror array lens **20** can have a polar array of the micromirrors **21**. Each of the micromirrors **21** can have a fan shape to increase an effective reflective area, which increases the optical efficiency.

The mechanical structures upholding each micromirror and the actuating components to rotate and translate the micromirrors **21** are located under the micromirrors **21** so

that the micromirrors **21** are to be closer one another thereby increasing the effective reflective area.

Fig. 6 illustrates how the micromirror array lens **23** gets an image. Arbitrary scattered lights **24, 25** are converged into one point **P** on the image plane by controlling the position of each of the micromirrors **26**. Phases of arbitrary lights **24, 25** can be adjusted to be the same by translating each of the micromirrors **26**. The required translational displacement is at least half of the wavelength of light.

The focal length **f** of the micromirror array lens **23** is changed by controlling the rotation and/or translation of the micromirror **26**. The operation of the micromirror array lens **23** is possible by controlling only rotation without controlling translation even though it can not satisfy the phase condition. In this case, the imaging quality of the lens **23** generated by controlling only rotation is degraded by the aberration. Pure translation without rotation can satisfy the two imaging conditions by Fresnel diffraction theory. The lens generated by the control of only translation has the aberration too. The smaller the sizes of the micromirrors **26** are, the less is the aberration. Even though the quality of the lens with one motion is lower than the lens with rotation and translation, the lens

with one motion has the advantage that its control and fabrication is easier than the lens with both rotation and translation.

It is desired that each of the micromirrors **26** has a curvature because the ideal shape of a conventional reflective lens **18** has a curvature. However, since the aberration of the lens with flat micromirrors **26** is not much different from the lens with curvature if the size of each micromirror is small enough, there is not much need to control the curvature.

Fig. 7 shows that an effective focal length and numerical aperture of the three-dimensional imaging device can be extended or changed by an auxiliary lens **27** having a predetermined focal length. An auxiliary lens **27** with large numerical aperture can increase numerical aperture of the three-dimensional imaging system. Also, the effective focal length of the three-dimensional imaging system can be changed to desired range by the auxiliary lens **27** and a micromirror array lens **28**.

The micromirror array lens is an adaptive optical component because the phase of light can be changed by the translations and/or rotations of micromirrors. The micromirror array lens can correct the phase errors as an adaptive optical component can correct the phase errors of

light introduced by the medium between the object and its image and/or corrects the defects of a lens system that cause its image to deviate from the rules of paraxial imagery. For an example, the micromirror array lens can correct the phase error caused by optical tilt by adjusting the translations and/or rotations of micromirrors. This allows magnification of any object within the Field of View without macroscopic mechanical motion of some portion of the optical system. Thus, the object to be magnified does not have to lie on the optical axis as in a conventional system.

The same phase condition satisfied by the micromirror array lens uses an assumption of monochromatic light. Therefore, to get a color image, the micromirror array lens of the three-dimensional imaging system is controlled to satisfy the same phase condition for each wavelength of Red, Green, and Blue (RGB), respectively, and the three-dimensional imaging system can use bandpass filters to make monochromatic lights with wavelength of Red, Green, and Blue (RGB).

If a color photoelectric sensor is used as an image sensor in the three-dimensional imaging system using a micromirror array lens, a color image can be obtained by processing electrical signals from Red, Green, and Blue

(RGB) sensors with or without bandpass filters, which should be synchronized with the control of micromirror array lens.

To image the Red light scattered from an object, the micromirror array lens is controlled to satisfy the phase condition for the Red light and Red, Green, and Blue image sensors measure the intensity of each Red, Green, and Blue light scattered from an object. Among them, only the intensity of Red light is stored as image data because only Red light is imaged properly. To image each Green and Blue light, the micromirror array lens and each imaging sensor works in the same manner with the process of the Red light. Therefore, the micromirror array lens is synchronized with Red, Green, and Blue imaging sensors.

While the invention has been shown and described with reference to different embodiments thereof, it will be appreciated by those skills in the art that variations in form, detail, compositions and operation may be made without departing from the spirit and scope of the invention as defined by the accompanying claims.